1. *Measurements upon the protanope.*—This is the type of red-green color blind who cannot see the far red spectrum at all.

a) He exhibits a change in foveal reflectivity upon "bleaching" with a bright light and subsequent "regeneration" in the dark, such as would be expected if what we were measuring was the density of a visual pigment.

b) The amount of bleaching produced is related to the energy of the bleaching light by the curve expected from photochemical theory.

c) Bleaching by red or green lights caused identical difference spectra; thus the protanope has only one visual pigment (in the red-green range). This would account for his monochromacy in this range if the pigment measured were that upon which vision depends.

d) The pigment measured is a *visual* pigment because red and green lights, which appear to the protanope identical, are found to bleach equally. And the difference spectrum coincides well with the protanope's luminosity curve.

2. *Measurements upon the normal eye.*—

a) A *deep* red bleaching light, which has no effect at all upon protanope pigments, gives, with the normal, a difference spectrum, indicating the presence of a red-sensitive pigment which the protanope lacks.

b) The total bleach in the normal shows the presence of a second photosensitive pigment, and this appears identical with that found in the protanope. Names for these two human cone pigments are "chlorolabe" (= green-taking), with maximum absorption at 540 mμ, and "erythrolabe," with maximum at 590 mμ.

c) In the normal there is somewhat less chlorolabe than erythrolabe, but in the protanope the amount of chlorolabe is about equal to the sum of all the pigments in the normal eye. It therefore seems that the protanope who has the normal number of cones is peculiar just in this—that those cones which in normal men contain erythrolabe have this pigment replaced by chlorolabe in the protanope.

[1] G. Wald, P. K. Brown, and P. H. Smith, *J. Gen. Physiol.*, **38**, 623–681, 1955.
[2] W. A. H. Rushton, *N.P.L. Symposium*, Paper I (London: H.M. Stationary Office, 1958).
[3] W. A. H. Rushton, *Proc. N.Y. Acad. Sci.*, **74**, 291–304, 1958.

COLOR VISION AND THE NATURAL IMAGE. PART I*

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We have come to the conclusion that the classical laws of color mixing conceal great basic laws of color vision. There is a discrepancy between the conclusions that one would reach on the basis of the standard theory of color mixing and the results we obtain in studying total images. Whereas in color-mixing theory the wave-lengths of the stimuli and the energy content at each wave-length are significant in determining the sense of color, our experiments show that in images neither the wave-length of the stimulus nor the energy at each wave-length determines the color. This departure from what we expect on the basis of colorimetry is not a small effect but is complete, and we conclude that the factors in color vision hitherto

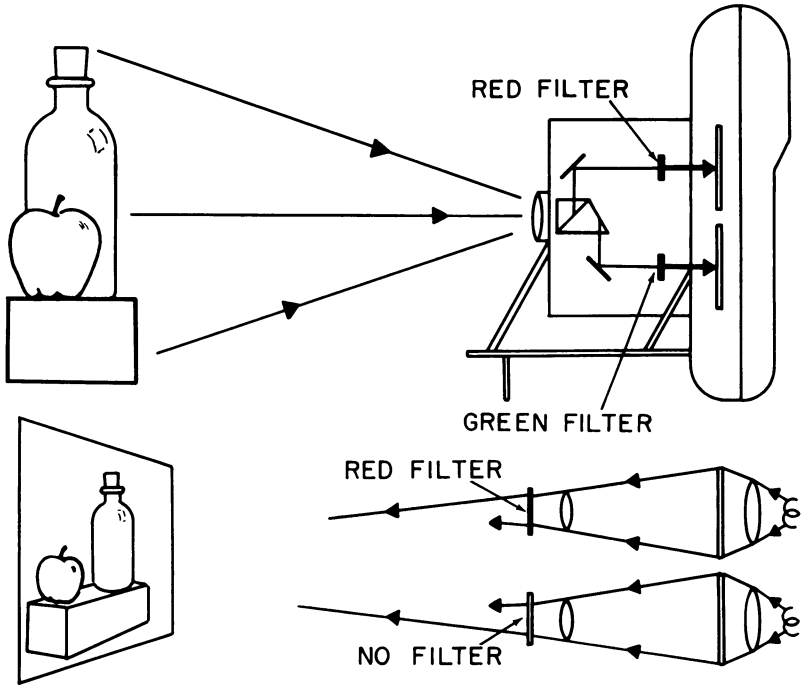

FIG. 1.—Diagram of camera and projector

regarded as determinative are significant only in a certain special case. What has misled us all is the accidental universality of this special case.

It was scientifically proper to base our earlier hypotheses about the functioning of the eye on our knowledge from this special case. Now, however, these recent experiments show that the special case is extraordinarily restrictive: The eye will see color in situations entirely unpredictable on the basis of older hypotheses.[1] Thus it may be necessary to build a new hypothetical structure to explain the

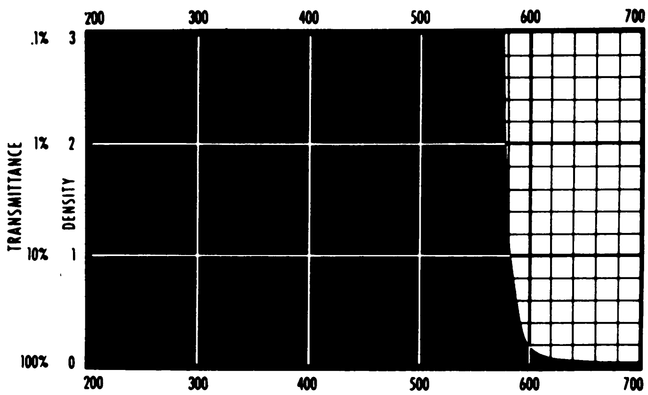

FIG. 2.—Kodak Wratten filter No. 24. Diagram of filter transmittance reprinted, with permission, from the copyrighted Eastman Kodak Company publication, *Kodak Wratten Filters for Scientific and Technical Use*. This applies also to Figs. 8, 9, 10, and 11.

mechanism for seeing color. The purpose of this paper, however, is not to discuss internal visual mechanisms, but rather to begin the description of the laws for a large *general* case—laws describing the relationship of the sense of color in the human eye to the structure of *total images*, laws in which wave-length of stimulus and intensity of stimulus will play entirely new roles.

APPARATUS

For these experiments two black-and-white photographic positive transparencies are made in a split-beam camera, so that they are taken at the same time from the same viewpoint through the same lens (Fig. 1). One is taken through a Wratten No. 24 filter, passing wave-lengths longer than about 585 mμ (Fig. 2), and one through a Wratten No. 58 filter, passing wave-lengths shorter than about 585 mμ. These two photographic records will be referred to hereafter as the "long record" and the "short record," respectively. The picture is exposed so that the gray scale appears to have the same densities in both records.

The two records are projected in a double-lens projector and superimposed exactly on a screen by means of a registration system. In front of each lens is a pair of polarizers mounted so that the intensity of the light in each beam can be varied separately. In projecting, the long record is projected ordinarily through a red filter (Wratten No. 24), and the short record through a neutral density filter of about 0.3 (when the polarizers are not being used). The half of the projector containing the long record will be referred to hereafter as the "long projector," and the other as the "short projector."[2]

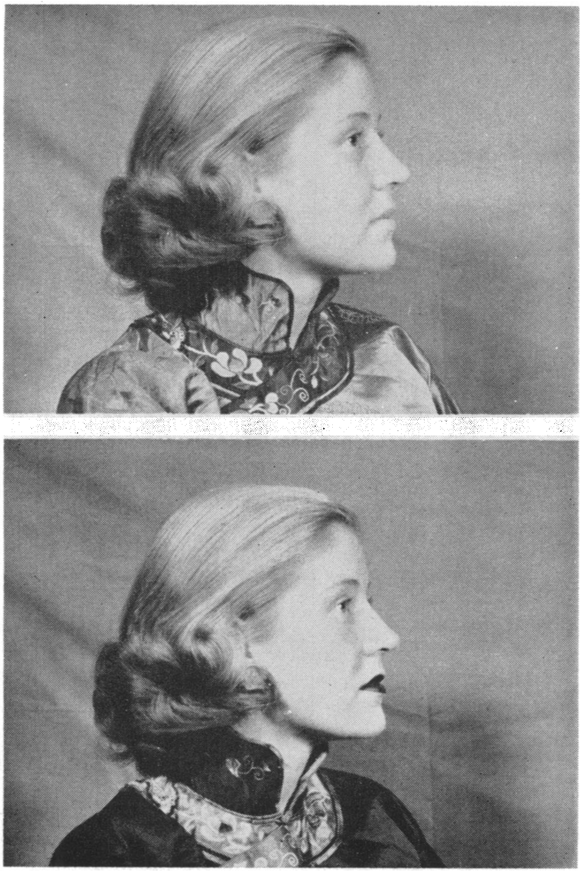

FIG. 3.—Blonde girl (Experiments 2, 3, 4, and 5). Upper image projected with longer wave-length stimulus; lower image with shorter wave-length stimulus. This applies also to Figures 4, 5, 6, 7, 12, and 13.

CHROMATIC PHENOMENA

The experiments demonstrated were the following:

Experiment 1.—The double projector is turned on, a filter transmitting red

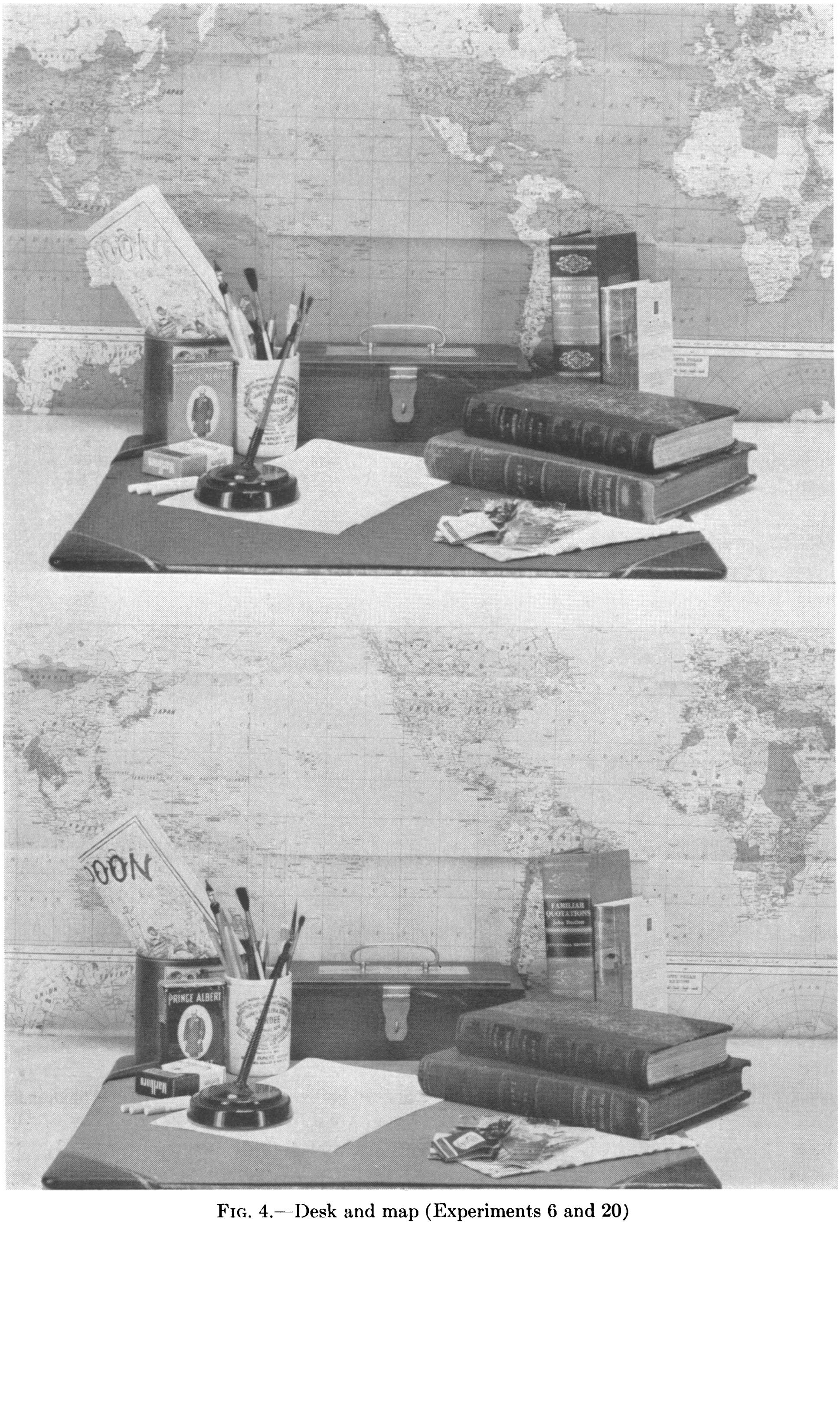

FIG. 4.—Desk and map (Experiments 6 and 20)

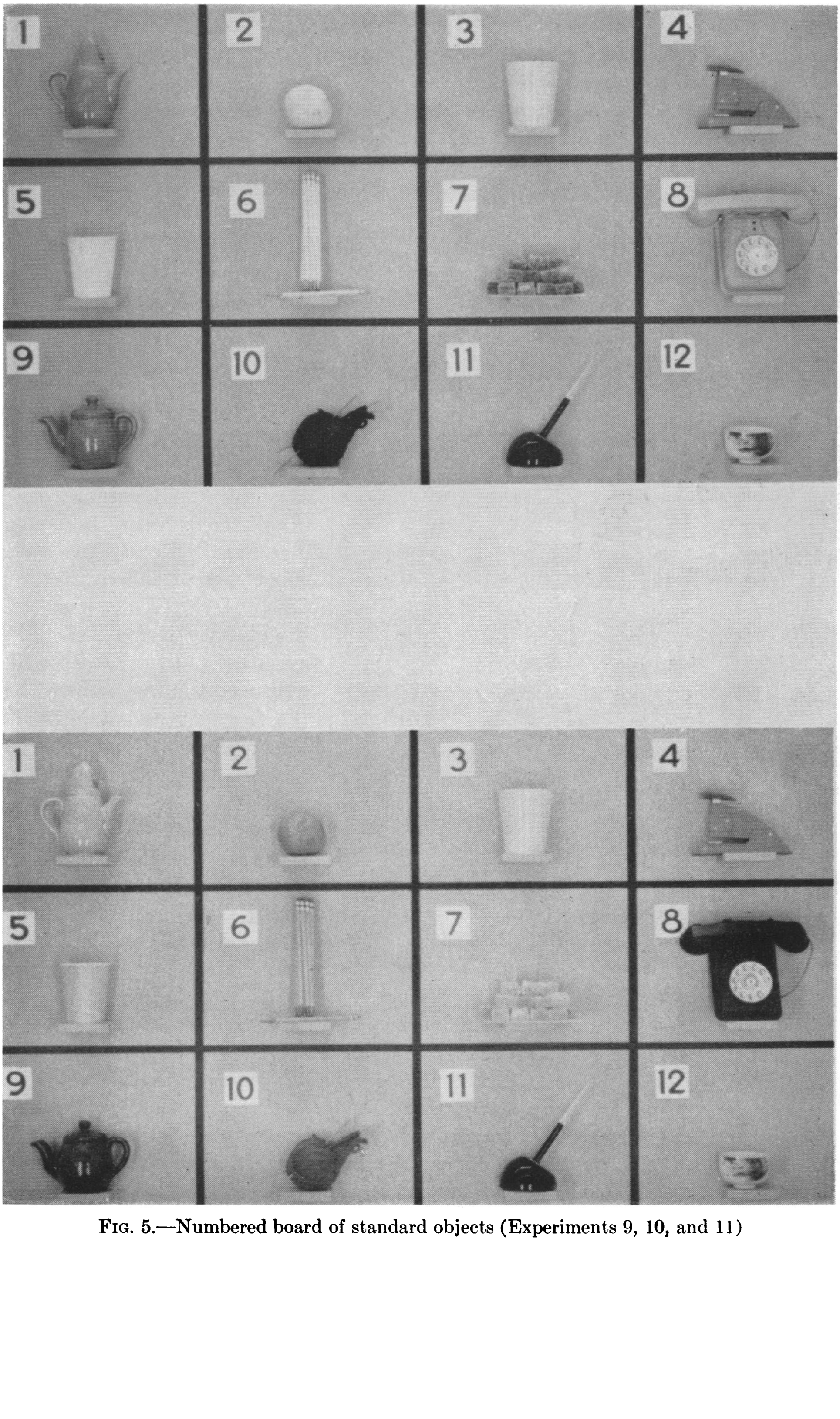

FIG. 5.—Numbered board of standard objects (Experiments 9, 10, and 11)

(Wratten No. 24) is placed over the lens of one projector and the polarizers are rotated to change the observed color of the screen from full white to full red, traversing the various shades of pink in between. Thus the screen is seen in the colors expected on the basis of classical color theory.

Experiment 2.—The red filter is removed, and the two components in Figure 3 are shown separately by occluding first one of the projectors and then the other, so that the audience may see the two black-and-white images produced by the beam-splitting camera. The differences to be expected in any color-separation photographs between the picture taken through the red filter and the picture taken through the green filter are pointed out to the audience.

FIG. 6.—Groceries (Experiment 12)

Experiment 3.—With the short projector occluded, the long record is shown projected through the red filter. Then the lens of the short projector is uncovered so that the black-and-white picture is combined with the red picture. Instantaneously the portrait appears in full color: blonde hair, pale blue eyes, red coat, blue-green collar, and strikingly natural flesh tones. (While it is not the primary purpose of these experiments to achieve verisimilitude, one is impressed by the frequent acceptability of this and many of the other pictures as lovely color photographs.)

Experiment 4.—The room lights are turned on full, flooding the screen with light, and it is shown that there is no visible time lapse between snapping off the lights and the appearance of full color in the picture.

Experiment 5.—The room lights are brought up from darkness to a medium level at which objects in the room can be clearly seen in color, but at which there is not so much light that the picture is washed out entirely. It is shown that the eye sees color in the room and color on the screen at the same time and that, furthermore, the colors on the screen are not changed by having the surrounding room illuminated in white light. This experiment gives the first premonition that multiple color universes can coexist side by side, or one within another.

Experiment 6.—In this picture (Fig. 4) the audience is to compare the pink states on the map with the yellow pencil; and the yellow pencil with the white pencil and the white marmalade jar which holds the pencils. It is pointed out that since classically all the colors on the screen would be pink, it is particularly important to note the difference between the pinks and the yellows and equally important to notice the strong sense of whiteness in the white objects. This is the first demonstration that it is not necessary to use traditional complementary colors to produce white, a fundamentally important fact in the image situation. The green-blue color of the large book entitled *Bartlett's Familiar Quotations* is contrasted with the deep-blue stripe on the air-mail letter, as well as to the blue tax stamp and the pale blue ocean on the map. The gamut of colors in this picture includes also the brown wooden box, the green blotter, the black inkstand, and the red lettering on the magazine. It is pointed out that this slide demonstrates dramatically that the transition from one stimulus (here, either red or white) to two (here, red *and* white) is the tremendous step: the full gamut of color appears. (The addition of a third stimulus does enrich the colors somewhat, but we do not know whether what is missing is due to inadequacy of technique or to the need of a little help from a third stimulus.)

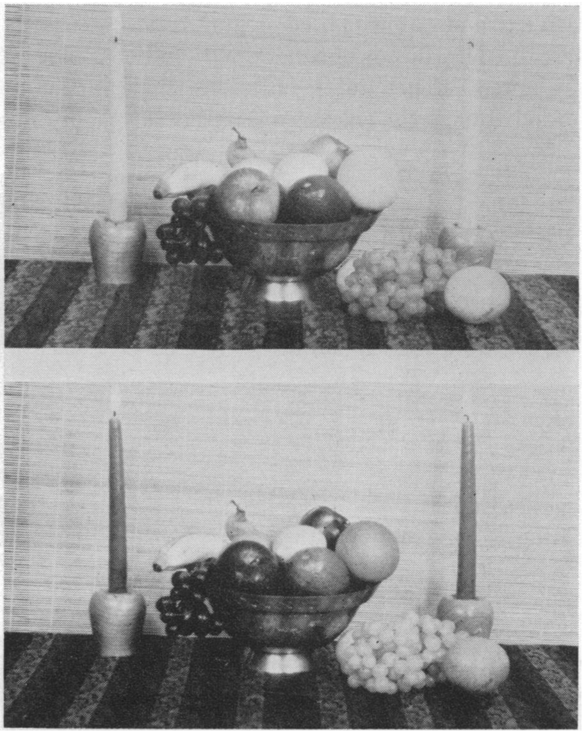

FIG. 7.—Bowl of fruit (Experiments 13, 14, 15, and 16)

Experiment 7.—A colorful picture, notable for the auburn red hair and the green sweater, is used to show that the field that counts in the image situation is not determined by angular subtend. The observer finds the sweater to be green even when he stands so close to the screen that the sweater fills a large portion of his field of view; and he also finds the sweater to be green when the image is made small and the observer is at a distance from the screen.

Experiment 8.—The same picture is shown with the red filter placed on the short projector, and with no filter on the long projector, except that the polarizers are turned to give the best color. The sweater is now reddish and the hair greenish, and the lips an intense blue-green, illustrating the phenomenon of hierarchical reversal, usual, to be sure, in any color photography system but particularly important here because it demonstrates that the colors are independent of what the observer expects, and that the system, in spite of use of the new "arbitrary" primaries, behaves like any system of color reproduction.

Experiment 9.—A slide is shown in which there are twelve colored objects photographed against a gray background divided into twelve numbered squares (Fig. 5).

It is pointed out that, except for the orange on square No. 2, each object could appropriately be any color, so that there can be no prior association between the name of the object and the name of the color of the object; thus one would not know that the telephone is red, the paper stapler gray, or the design on the teacup, on square No. 12, dark blue. It is pointed out that this slide had been used to interrogate naive observers, and that, except for the color-blind, marked consistency was found in their reporting of the color names.

Experiment 10.—Using the same standard-objects slide as for Experiment 9, a pair of polarizers is placed in position in front of each projector, the relative brightness is varied from the position in which only the red image shows, to the position where just the white image shows. The audience is asked to indicate the two extremes at which color first appears; that is, with only the red image on the screen, the white is slowly added, and the colors at the point where they first appear are noted. Then, with only the white image on the screen, the red is slowly added, and as the colors appear they are again noted. It is pointed out that when

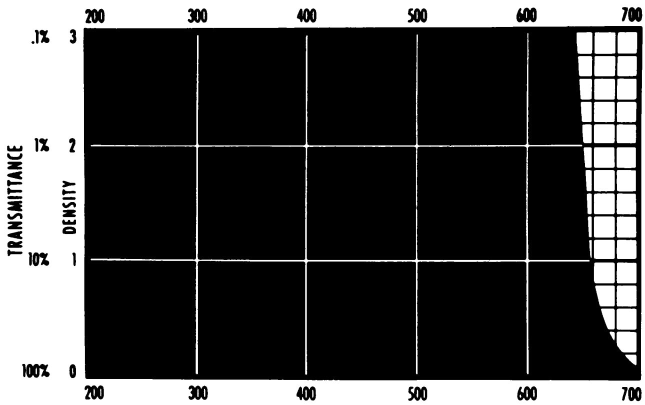

FIG. 8.—Kodak Wratten filter No. 70

color does appear at both extremes it appears at the same time for all the objects on the slide. It is demonstrated that the ratio of stimuli can be varied enormously —with some pairs of stimuli by ratios as high as 100 to 1—without altering the color name given to each one of the objects.

Experiment 11.—In this experiment a duplicate of the short record is superimposed on the short record already in the projector, thus doubling its contrast. A single long record is used, so that it has the original contrast of the previous experiments. Thus for the short record in places where, in the previous experiments, a fifth of the light was transmitted, the slide now transmits a twenty-fifth; in places where a tenth was transmitted, the slide now transmits a hundredth; in places where all the light was transmitted, the slide now transmits all the light. Since no change was made in the long record, the same amount of light is transmitted by it as was transmitted in the earlier experiments. It follows, therefore, that for each object on the slide there is now a new ratio of long to short stimulus, and it would be expected classically that each object would now be a new color. Actually, the objects retain their original color names, demonstrating the stability of the colors of an image with respect to the contrast of its component images, and illustrating further that color is independent of the quantity of the stimulus defined locally. It is pointed out that we must not let the casualness of the statement that we have doubled contrast in one image without doubling it in the other obscure in our minds the amazing fact that utterly new pairs of ratios give the same colors in the same places.

Experiments 12, 13, 14, and 15 are designed to demonstrate further that color at a point in an image is independent of the wave-length composition of the radiation

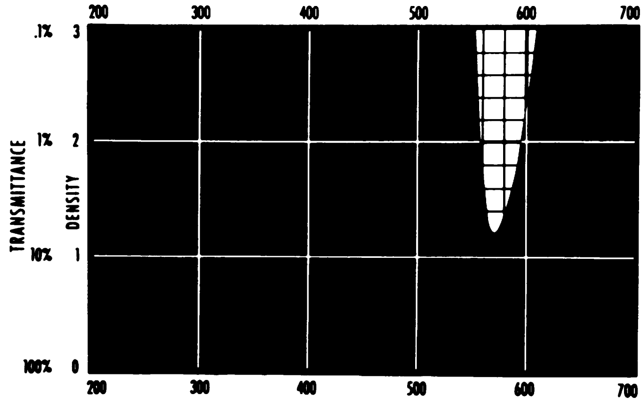

FIG. 9.—Kodak Wratten filter No. 73

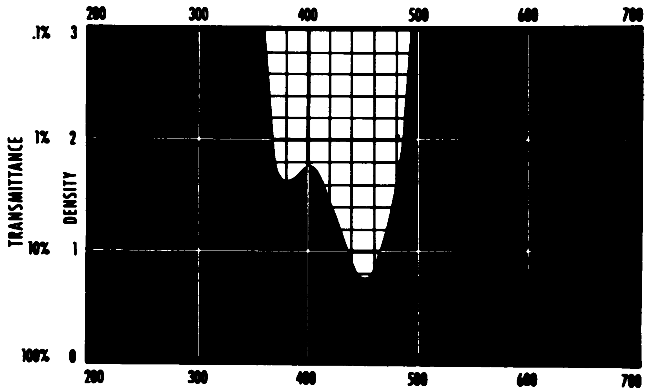

FIG. 10.—Kodak Wratten filter No. 49B

coming from that point. While with changes of filters there is a slight over-all wash of color in extended background areas, objects retain their original color identity. (Many of the audience sitting off the axis of the projector are unable to witness the following four experiments because of the extremely low light level resulting from the dark filters.)

Experiment 12.—A slide showing multicolored groceries on a table top (Fig. 6) is shown with Wratten No. 24 and no filter on the one hand, and on the other hand with Wratten Nos. 24 and 58.

Experiment 13.—A bowl of fruit on a table top (Fig. 7) is shown with Wratten No. 70 (Fig. 8) and Wratten No. 73 (Fig. 9).

Experiment 14.—The slide in Experiment 13 is shown with Wratten No. 73 and Wratten No. 49B (Fig. 10).

Experiment 15.—The same slide is shown with Wratten No. 47B (Fig. 11) and no filter.

Experiment 16.—It is demonstrated to the audience that the filter Wratten No. 73 which passes a narrow band of yellow may be used as a shorter member of a wave-length pair, and as a longer member of a wave-length pair, depending on what is picked to go with it. (*Note:* Experiments 13 and 14.)

ACHROMATIC PHENOMENA

Experiment 17.—Three identical black-and-white transparencies are used, two in superposition on each other in one projector, one in the other projector. These are projected with red and green filters, and the question arises: What colors should one expect? One expects color for two reasons, either classically because of the

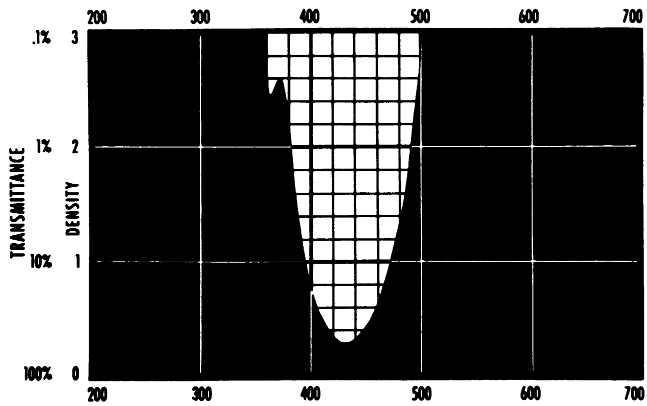

FIG. 11.—Kodak Wratten filter No. 47B

varieties of ratios of red to green or in terms of our new approach because the numerical value of many of the ratios are equal to ratios which existed in the image which showed color in Experiment 9. Actually, one finds that the whole slide is uniform in color and nearly colorless, even though many of the ratios of stimuli for the various objects are the very ratios that existed when the slide appeared in full color.

Experiment 18.—The short record is placed in the short projector and no record is placed in the long projector. One sees the wash of red light over the image from the short projector. The polarizer on the long projector is varied over its range. In spite of the fact that all possible ratios of stimuli have been on the screen, there appears only a uniform wash of the colors in their classical mixtures.

Experiment 19.—Another class of achromatic phenomena is introduced by this experiment in which a photographic step-wedge, running horizontally, is placed in one projector, and a step-wedge, running vertically, is placed in the other projector. Thus, in superposition on the screen, the wedges create 256 possible ratios of the two stimuli, arranged, however, in a geographically systematic way. The colors mix only in a classical sense, red and white giving a vague pink, and red and green showing some red, some green, and some yellow.

Still another class of nearly colorless situations is exemplified by Experiments 20 and 21.

Experiment 20.—The map slide (Fig. 4) is projected with the long and short record far out of registration. The gamut of colors is strongly restricted. While going beyond the classically expected colors, there is only the smallest suggestion of the new colors which here are few and unsaturated. The images are slowly brought into registration. At the instant of perfect registration, the full gamut of color snaps into appearance.

Experiment 21.—A picture of one scene is placed in the long projector, and a picture of a different scene is placed in the short projector. The limitations on color are similar to those in Experiment 20: there is almost none.

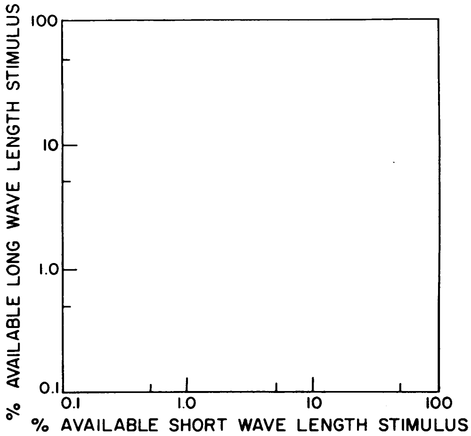

FIG. 12.—Co-ordinate system

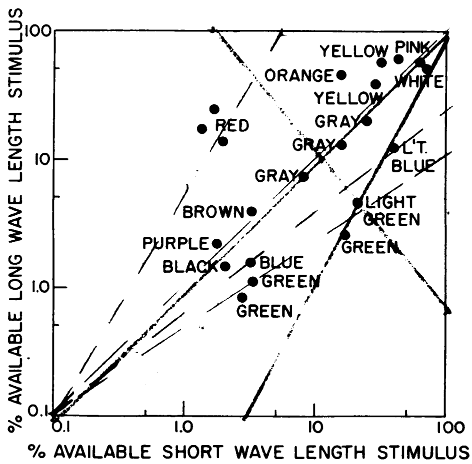

FIG. 13.—Co-ordinate system with loci of colors

A NEW CO-ORDINATE SYSTEM

A new co-ordinate system is shown which describes color in images and which predicts the achromatic situations (Fig. 12). A remarkable thing about the new co-ordinate system is that it is physically dimensionless, involving a ratio of ratios and holding constant an arbitrary pair of wave-lengths. In this co-ordinate system the percentage of available short-wave stimulus is plotted against the percentage of available long-wave stimulus.[3] The first message of the co-ordinate system is that color in an image is indeed independent of the over-all flux in the individual component images and, second, that the color at a point in an image is independent of the wave-lengths of the radiation at that point. This is true of what is seen with a large variety of pairs of wave-lengths and relative brightnesses. Part II of this paper will show that the gamut of colors is restricted when some pairs of wave-lengths are used, and that there are levels of relative energies at which there are significant color shifts. However, even in these situations, the color is not at all the classical function of wave-length and relative energy.

We now study our twenty-one experiments in terms of the co-ordinate system. Slides such as those in Figures 3, 4, 5, 6, 7, and 17 are measured as indicated above, and the results are shown in Figure 13. Here we see that in this new dimensionless co-ordinate system the grays fall on a straight line at an angle of 45° to the axes, warm colors being to one side of the gray and cools to the other.

Doubling the contrast of the image, as in Experiment 11, rotates the gray line, which carries with it the family of warm and cool colors, disposed as they were originally on either side of the gray line; in Figure 14 imaginary lines have been drawn through some of the colored areas, the unbroken lines representing points in an image of normal contrast, the dotted lines indicating the new position of those points when the contrast of one of the images has been doubled. The significant fact is that the colors themselves remain constant for the observer, in spite of this translation in the co-ordinate system, as if the eye were indifferent to the change

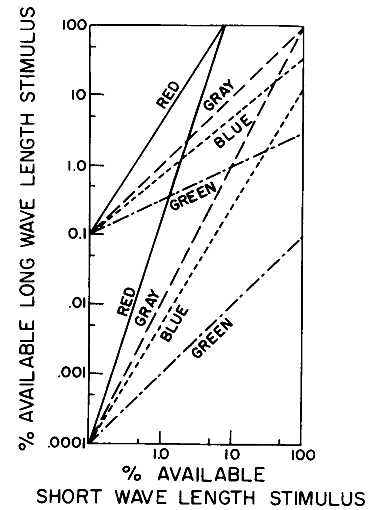

FIG. 14.—Elastic transformation of co-ordinate system effected by doubling contrast in one image.

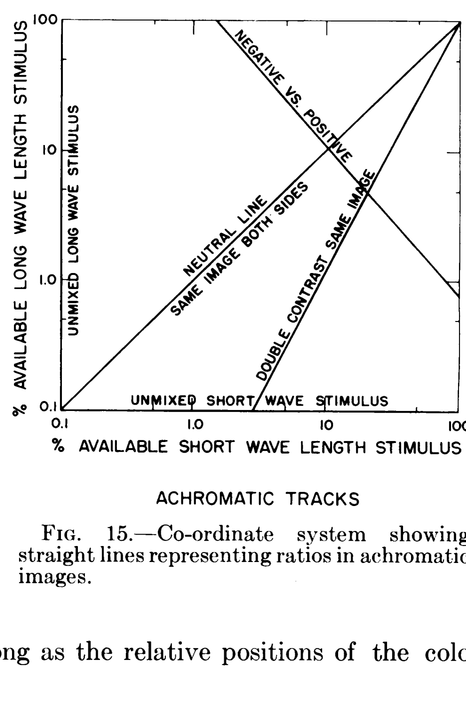

FIG. 15.—Co-ordinate system showing straight lines representing ratios in achromatic images.

in position of the array as a whole as long as the relative positions of the color points in the array remain unchanged.

Achromatic Situations.—When the points in the images in Experiments 17 and 18 are plotted on the diagram they are found to fall on straight lines (Fig. 15), suggesting that this is the criterion for whether or not an image is achromatic, and possibly suggesting further that if the points measured in an image fall on any smooth continuum in the diagram, such an image may also be achromatic. For three identical images in Experiment 17 all the points fall on a line (which is in the same position as the gray line in the double-contrast image of Experiment 11). When a single image in one projector is combined with a wash of light in another, as in Experiment 18, the measured points will fall on the straight line parallel to one of the axes. As the observer's eye moves over the field of the crossed wedges in Experiment 19, in any direction, the points traversed, when measured, will fall on simple smooth curves on the diagram of the co-ordinate system.

If the wedges were continuous instead of being step-wedges, then one might think of the crossed wedges as being the continuum which is the co-ordinate diagram as a whole.

The last class of situations, which are nearly colorless, includes the out-of-register images of Experiment 20 and the two different images of Experiment 21. If one thinks of the fusion of the components of the colored image on the retina as being analogous to the central fusion of the two members of the stereoscopic pair on the two different retinas, then it seems plausible that the sense of color might be greatly

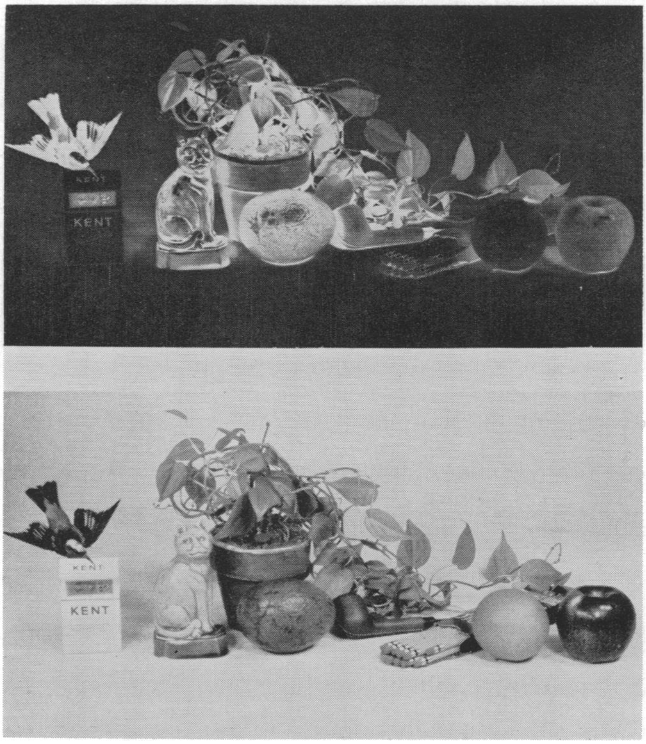

FIG. 16.—Spectrum of natural objects, negative and positive

diminished when the component images on one retina are out of register, just as the three-dimensional sense will be greatly diminished, indeed destroyed, if the members of the stereoscopic pair do not lie in "registry" on the corresponding points of the two retinas. A second way of thinking, which will not be discussed in this paper, has to do with the relationship between the way the eye moves over the geography of the image and the trace of the point on the geometry of our diagram.

Experiment 22.—To test the hypothesis that continua in general, and straight lines in particular, have a special significance in our co-ordinate system, one may ask the following question: If the measured points in the image fall on a straight line at *right* angles to the 45° line in the co-ordinate system, what colors will appear? Now if a negative image is placed in one projector and the positive from that negative is placed in the other projector (Fig. 16), then the measured points *will* fall on a line at right angles to the 45° line. The red filter is placed on the long projector and no filter is placed on the short projector; the negative and positive images are registered carefully. Is the co-ordinate system a good prophet? All ratios of stimuli are present in these images which are geometrically identical and in register. Will this be an image in good color, or will it be essentially colorless? The answer is that the co-ordinate system *is* a good prophet. There are only reds and whites, and a little pinkness. This is further support for the hypothesis that stimuli whose measurements are disposed on a straight line in our co-ordinate system do *not* "mix" to give color. (The control picture, the two positives taken and

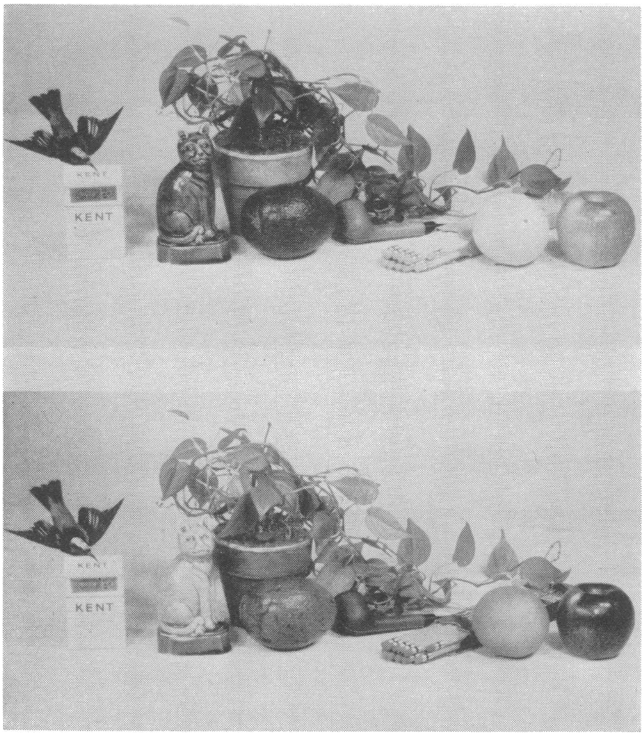

FIG. 17—Spectrum of natural objects, control.

shown in our new "standard" way [Fig. 17], is vividly colored.) This negative-positive pair promises to be one of the great clues to the nature of color vision. It will be discussed in the next part of this paper.

Because of the limitations of flexibility imposed by using filters, a dual monochromator has been built since the time of the symposium. The work with this instrument has supported the experiments shown at the symposium and has enabled us to arrive at a meticulous description of the separation of wave-lengths, as a function of wave-length, that is required to see the gamut of colors for experiments like those described above. This instrument and the detailed results obtained with it will be described in Part II. There will also be described new apparatus demonstrated at the meeting of the Optical Society of America on October 9, 1958, which enables an audience to see that the same monochromatic stimulus can be either the long or short member of a pair of stimuli. The demonstrations given at the Physics Colloquium, Harvard University, on November 17 and 18, 1958, showing how the eye functions to see full color in a universe involving only a narrow wave-length band ("Johnny's Magic Bookcase") will be described, and the generalization will be drawn that our everyday world is just a special case among these universes.

Part III will continue the discussion of the nature of the field in the image situation and the relationship of the spectrum to color vision.

* This paper will be in several parts, the first of which is this symposium. Part I then contains the experiments up to the time of the symposium, April 28, 1958.

[1] The work in this paper should not be confused with experiments such as those of Hess, which describe how a stimulus of a particular wave-length looks differently colored when viewed after the eye has been exposed to another wave-length for a significant period of time (*Arch. Ophthalmol.*, **36,** I [1890]). Nor should it be confused with those theories which explain the phenomenon which Hess measured, and other allied phenomena, as the result of fatigue of the eye to various states of chromatic adaptation.

The colors described in our experiments appear immediately, and do not alter appreciably with time, and we do not seek to explain them as effects of adaptation. To the best of our knowledge the gamut of color is much larger than that noticed by Hess or predicted by any theory concerning chromatic adaptation; our newly discovered achromatic situations are not predicted by any previous theories; nor is there any basis in those theories for our dimensionless co-ordinate system (see below). Furthermore it seems that none of the previous work in any kind of color matching or system of complementary colored shadows (Goethe) can be the basis for the observed fact that the colors in our images, arising from unorthodox stimuli, correspond in hierarchical order to the colors that the observer would have seen had he been at the original site.

[2] Earlier studies in two-color projection were done by Fox and Hickey who found that moving pictures which showed some color could be taken by alternately photographing through no filter and through a filter which transmitted red light, and by projecting correspondingly (British Patent No. 636, issued July, 1914, to William Francis Fox and Wm. H. Hickey, *Improvements in Kinematographic Apparatus*). Some years later Bernardi used red and green filters for taking movies and red and white for projecting (Adrian Cornwell-Clyne, *Colour Cinematography* [London, 1951], p. 261).

[3] This means that one measures the amount of light on the screen for the long wave-length image in the brightest place and takes that as 100; then one measures the amount of light for that long record alone at another place in the image and makes the percentage. Then that percentage is plotted against the percentage of available light for the short record alone at the same point on the screen. The ratio of these two percentages describes the color at that point.